Resonant Extraction from the Debuncher for Mu2e

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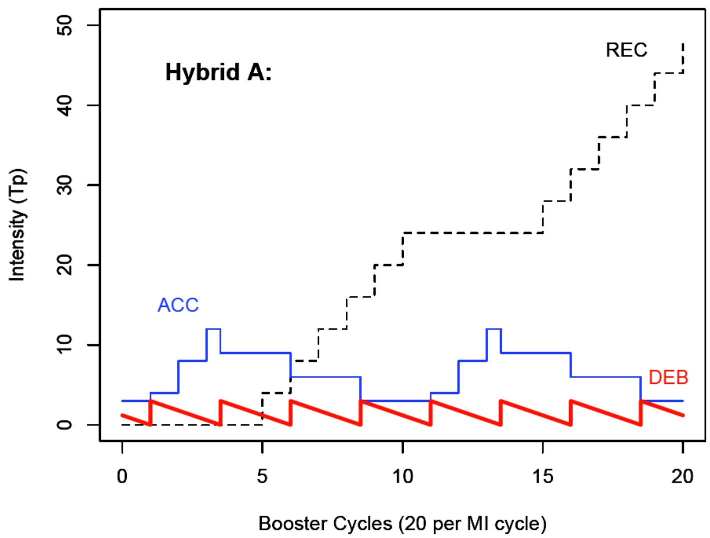
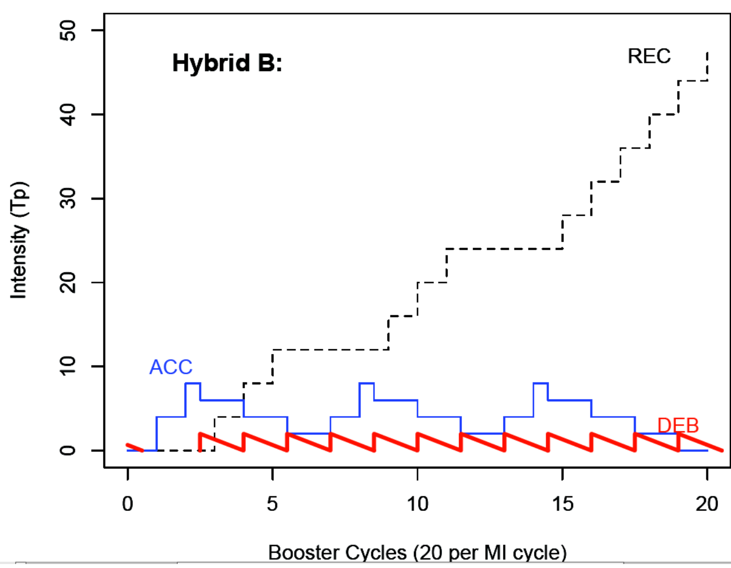
Dave Wildman

November 22, 2010

The two “hybrid” scenarios





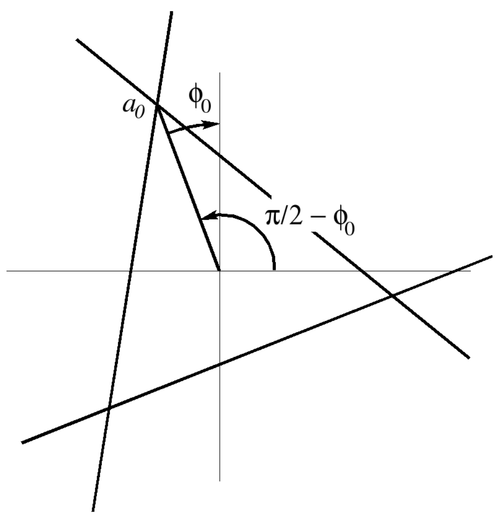
- A: $3 \times 10^{12}/166.67$ msec B: $2 \times 10^{12}/100$ msec
  $\Rightarrow \ \langle dN/dt \rangle = 18 \times 10^{12}/$ sec, in each scenario.
- Replaced the dreaded “baseline scenario” of 2008-2009.

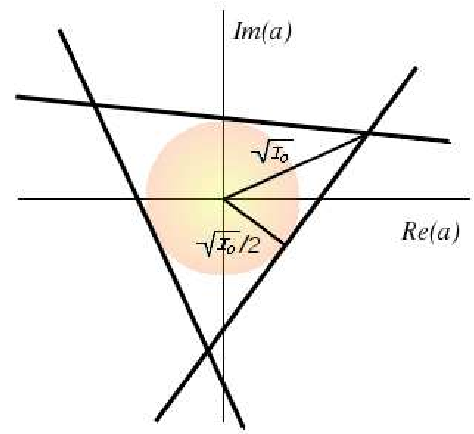
Some parameters

Quantity	Unit	Value
Beam		
Kinetic energy	Gev	8
Momentum	GeV/c	8.88889, 8.88626[a]
$B\rho$	T-m	29.6501[d]
$(\beta, \gamma, \beta\gamma)$		(0.994, 9.526, 9.474)[d]
$(\Delta E)_{\text{max}}$	MeV	100[k]
$(\Delta p/p)_{\text{max}}$		0.0113[d]
$(\Delta t)_{\text{rms}}$	nsec	20-50[f] (nominal: 40)
Initial emittance	π mm-mr	10-25 / $\beta\gamma$
Intensity	Tp (10^{12} protons)	3[b], 2[c]
Debuncher		
Circumference	m	505.283, 505.294[a]
Rev. period	μsec	1.695[d], 1.685[f]
Rev. frequency	kHz	590.038[d], 590.018[a]
Spill time[g]	msec	166.67[b], 100[c]
N_{turns}/spill		98,328[b], 58,997[c]
$\langle dN/dn \rangle$	Mp (10^6 protons)	30.51[b,d], 33.9[c,d]
$\langle dN/dt \rangle$	Tp / sec	18[d,h]
Resonant tunes		29 / 3[i], 19 / 2[j]
Acceptance	π mm-mr	335[a]/$\beta\gamma$
RF		
Harmonic number		4
Frequency	MHz	2.36[d]
Voltage	kV	32

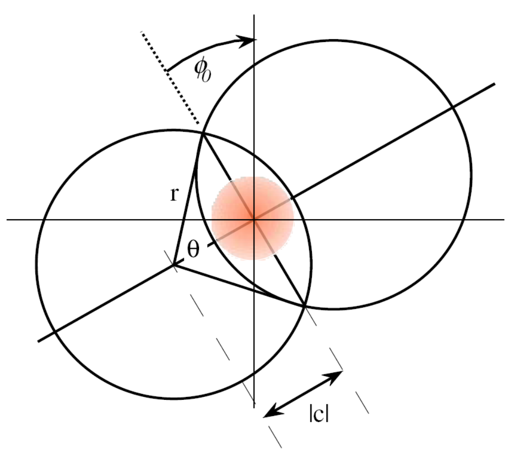
[a] Taken from Steve Werkema's presentation of November 18, 2008.
[b] Hybrid A scenario.
[c] Hybrid B scenario.
[d] Calculated from other parameters.
[e] Tentative value, from 2008.
[f] From Mike Syphers' Mu2e-doc-585-v3
[g] These numbers assume a 15 Hz Booster cycle. This is the total time alloted to extract beam. It should be reduced by $\approx$ 10% to allow for setup before and cleanup after extraction.
[h] The gap in Hybrid B must be taken into account.
[i] Third integer.
[j] Half integer.
[k] This refers to the full width; that is, $(\Delta E)_{\text{max}} = 2(E - E_0)_{\text{max}}$
[l] For third-integer extraction: 393 kHz $\approx (2/3) \cdot 590$ kHz

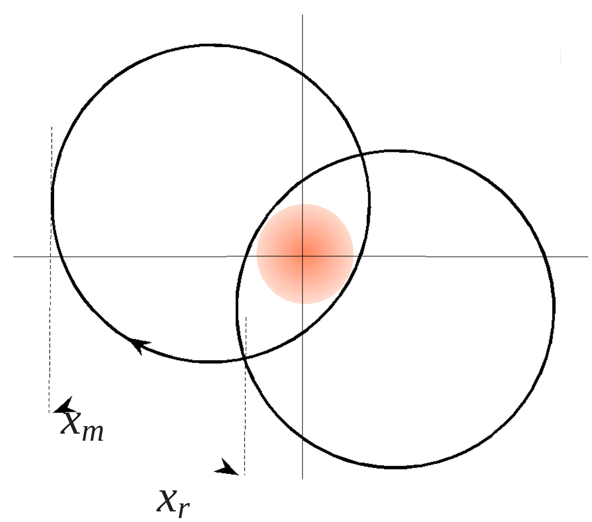
Two resonances; horizontal phase space





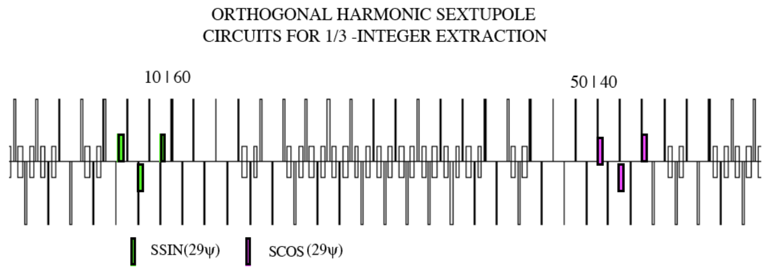
- Third-integer resonance separatrix



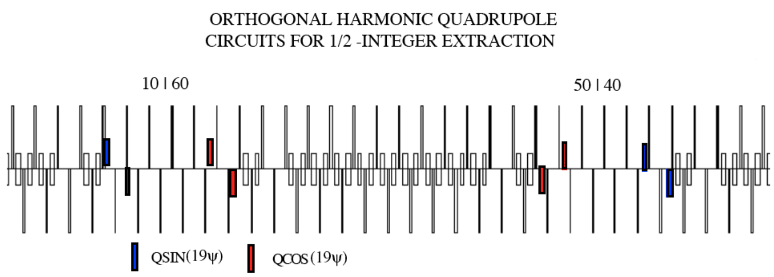


- Half-integer resonance separatrix

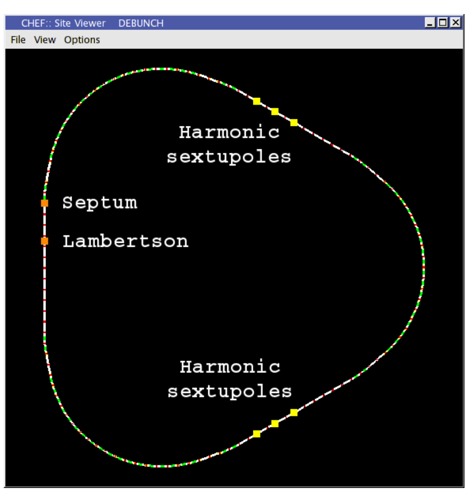
Harmonic sextupoles and quadrupoles



- Location of harmonic sextupoles on two orthogonal circuits configured for third-integer resonance extraction.

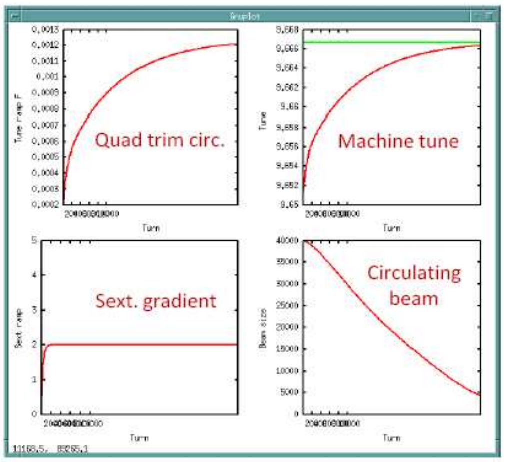


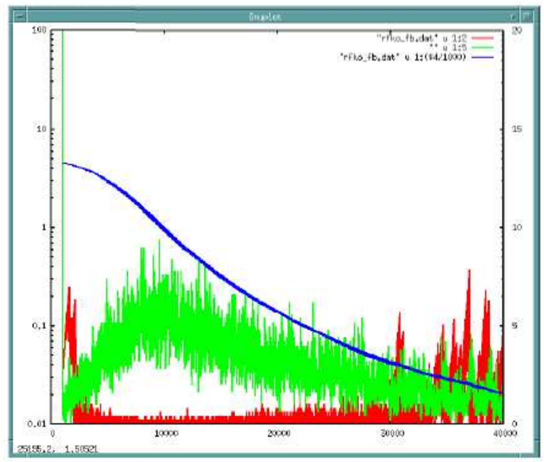
- Location of harmonic quadrupoles on two orthogonal circuits for the half-integer configuration in which the straight sections' cells have been set individually to 60^o, as in the arcs.

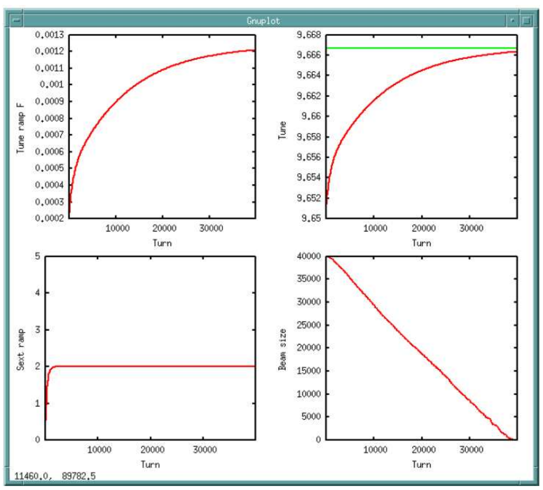


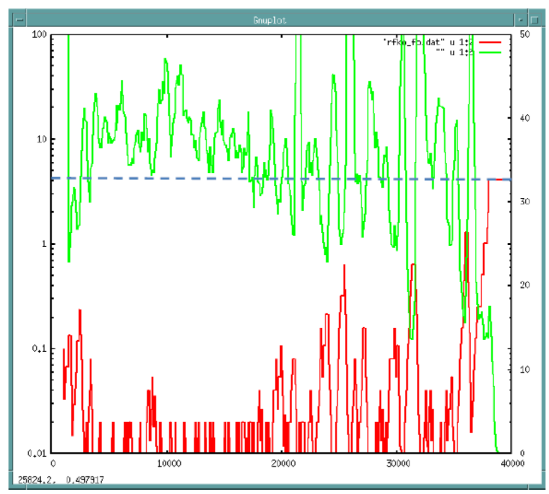
- Oh, yes . . . there is a septum and a lambertson too.

Anticipated VG: Simulation of third-integer extraction including space charge





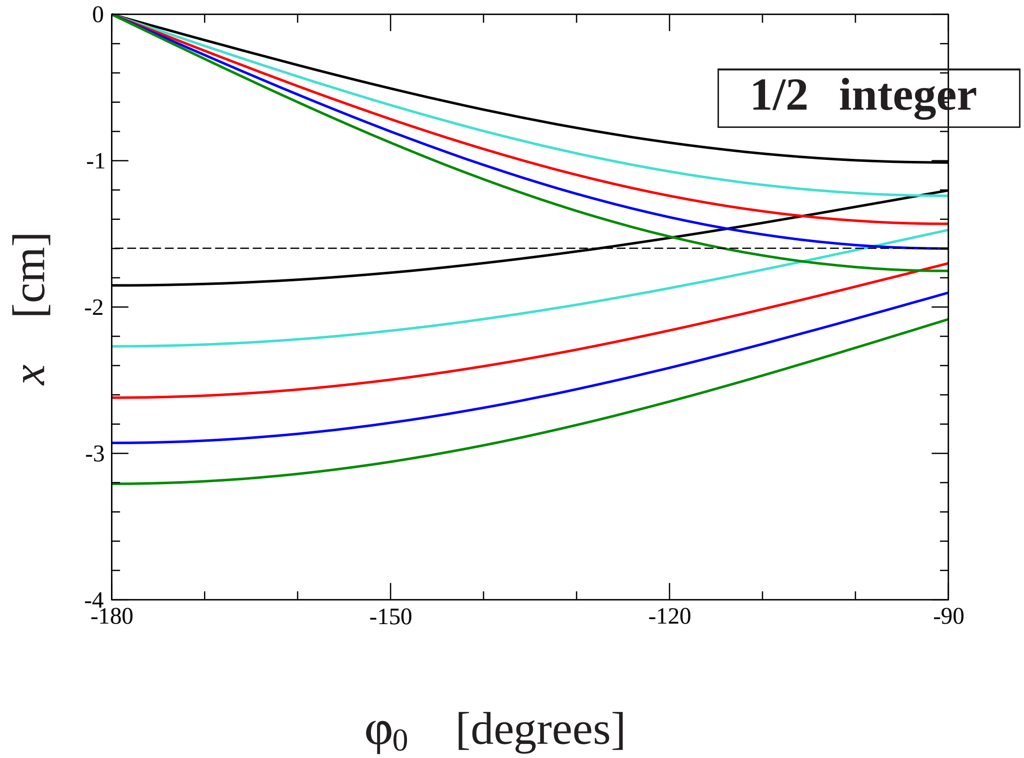


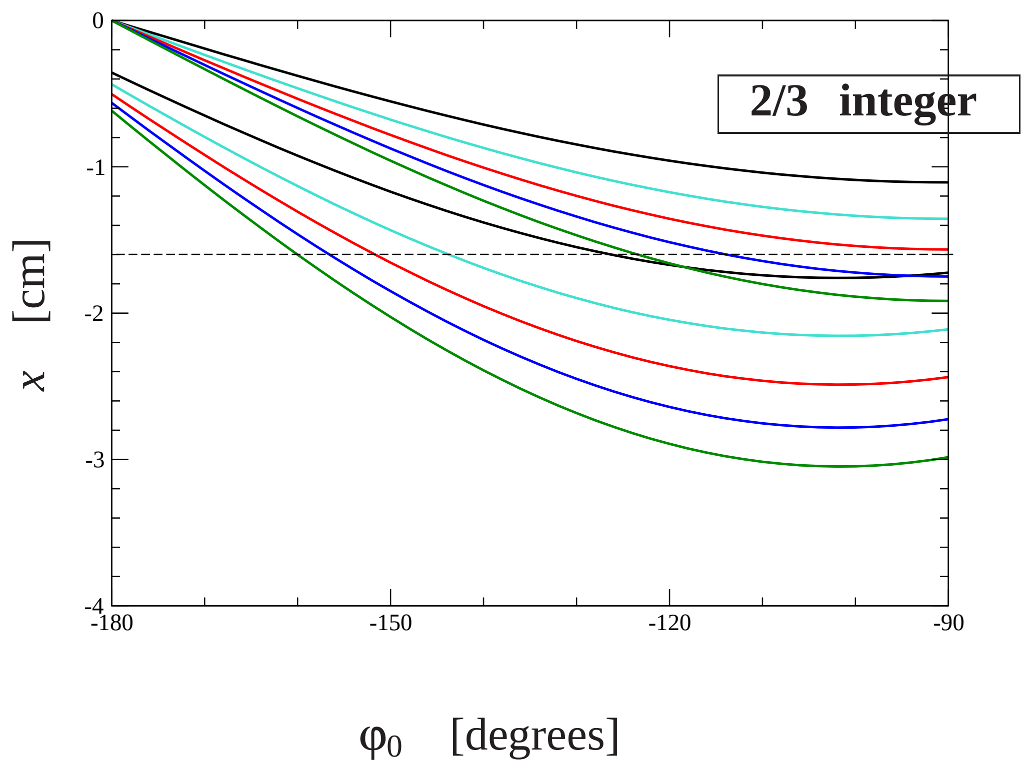


- On the left are plots of the quadrupole circuit ramp, tune, sextupole ramp, and beam intensity during the spill. On the right, the green trace shows the turn-by-turn structure of the spill, while the red follows the field strength, on a log scale, of the RFKO oscillator.

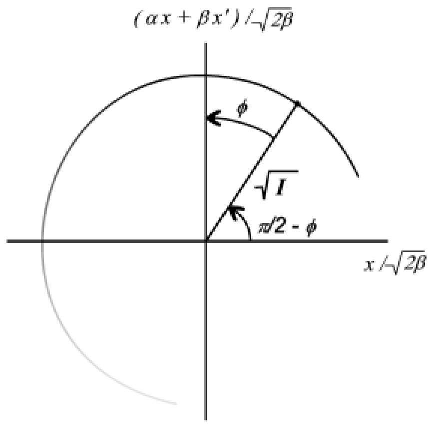
- RFKO by itself is not strong enough to control fully the spill rate; micro-adjustment of the tune ramp is needed.

Orbit bounds

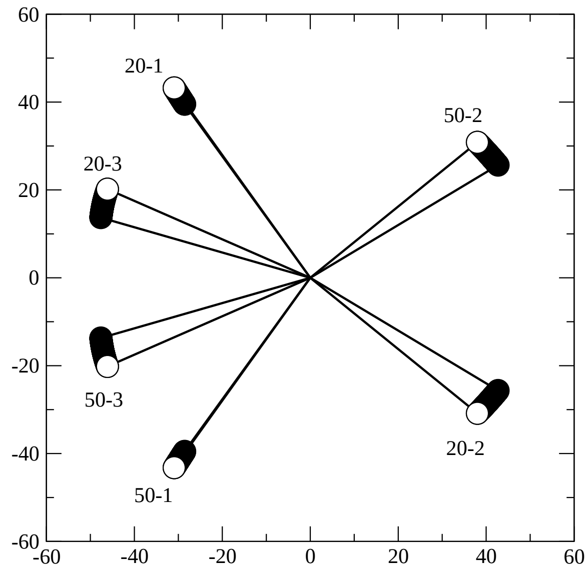




Phasor stability of third-integer resonance



$$\sqrt{2\beta}\, a \;=\; x + i(\alpha x + \beta x')$$



- Hamiltonian exemplar for third-integer resonance:

$$\begin{aligned} H &= \Delta\nu\, a^* a - iga^3 + ig^* a^{*3} + \cdots \\ &= \Delta\nu\, I - \left(g e^{-i3\varphi} + g^* e^{i3\varphi} \right) I^{3/2} + \cdots \quad . \end{aligned}$$

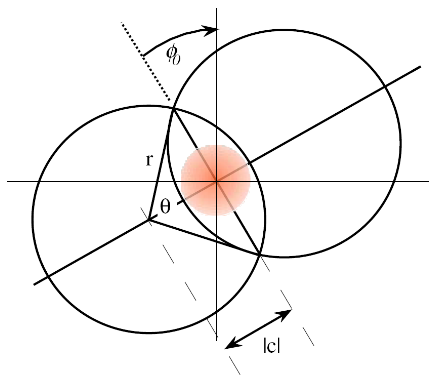
- $\Delta\nu = \nu_x - 29/3 \approx 0$ is the difference between the linear (small amplitude) horizontal tune and the resonant tune and is presumed to be small; the "resonance coupling constant," g, is a linear functional of the sextupole field strength distribution.

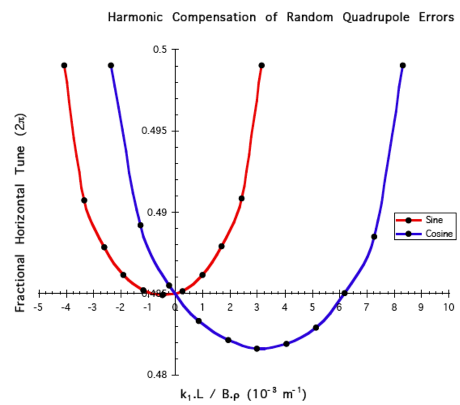
$$g \;=\; \frac{i}{6\sqrt{2}}\, \frac{1}{4\pi} \sum \frac{B''l}{B\rho}\, \beta_1^{3/2}(\theta)\, e^{-i3(\psi_1(\theta) - \Delta\nu\cdot\theta)}$$

- The phase of the complex parameter g determines the orientation of the third-integer separatrix: $|a_0|\, e^{i3\varphi_0} = \Delta\nu/(3g^*)$.

- The phasors in g's summand are reasonably stable during the squeeze. Thus, there should be no need for sextupoles to "track" the tune.

Half-integer resonance exemplar





- Hamiltonian exemplar for half-integer resonance:

$$H = (\Delta\nu - G_2 e^{-i2\varphi} - G_2^* e^{i2\varphi}) I + G_4 I^2 + \cdots ,$$

where $\Delta\nu \equiv \nu_x - 19/2 \approx 0$ is “small,” and

$$G_2 = \frac{1}{8\pi} \sum_{\text{quadrupoles}} \frac{\delta B' l}{|B\rho|} \beta_x \, e^{-i2(\psi_x - \Delta\cdot\theta)}$$

$$G_4 = \frac{1}{32\pi} \sum_{\text{octupoles}} \frac{B''' l}{|B\rho|} \beta_x^2$$

- The expression “ $\delta B'$ ” indicates that only the fraction of quadrupole strength *not contributing at first order to the tune* must be used in the summand for G_2.

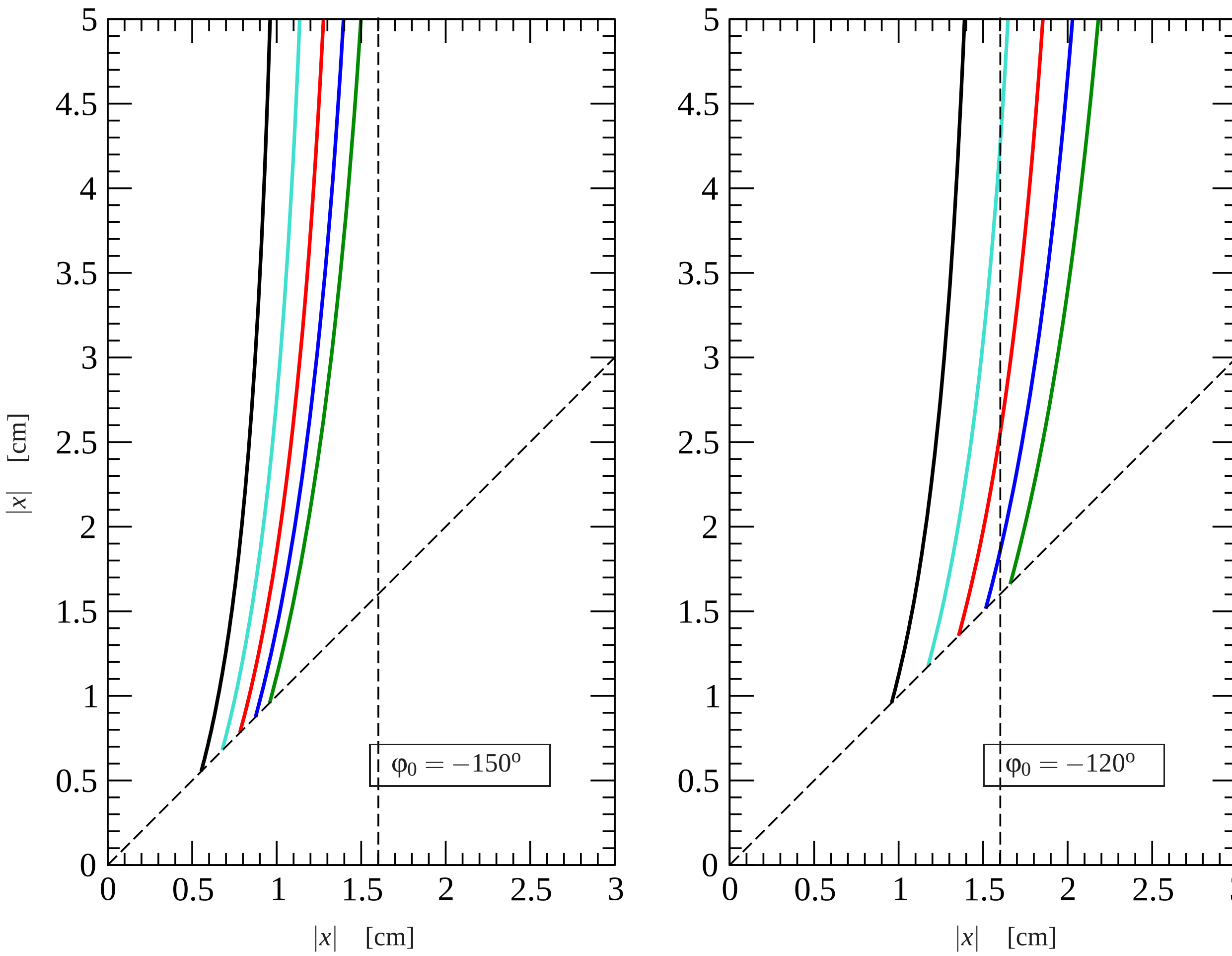
$$r^2 = -\Delta/2G_4 ,$$

$$c^{*2} = -G_2/G_4 , \text{ and}$$

$$|a_0|^2 = r^2 - |c|^2 = -\frac{\Delta}{2G_4} - \frac{|G_2|}{|G_4|} = \frac{\text{sgn}(\Delta)\cdot 2|G_2| - \Delta}{2G_4} .$$

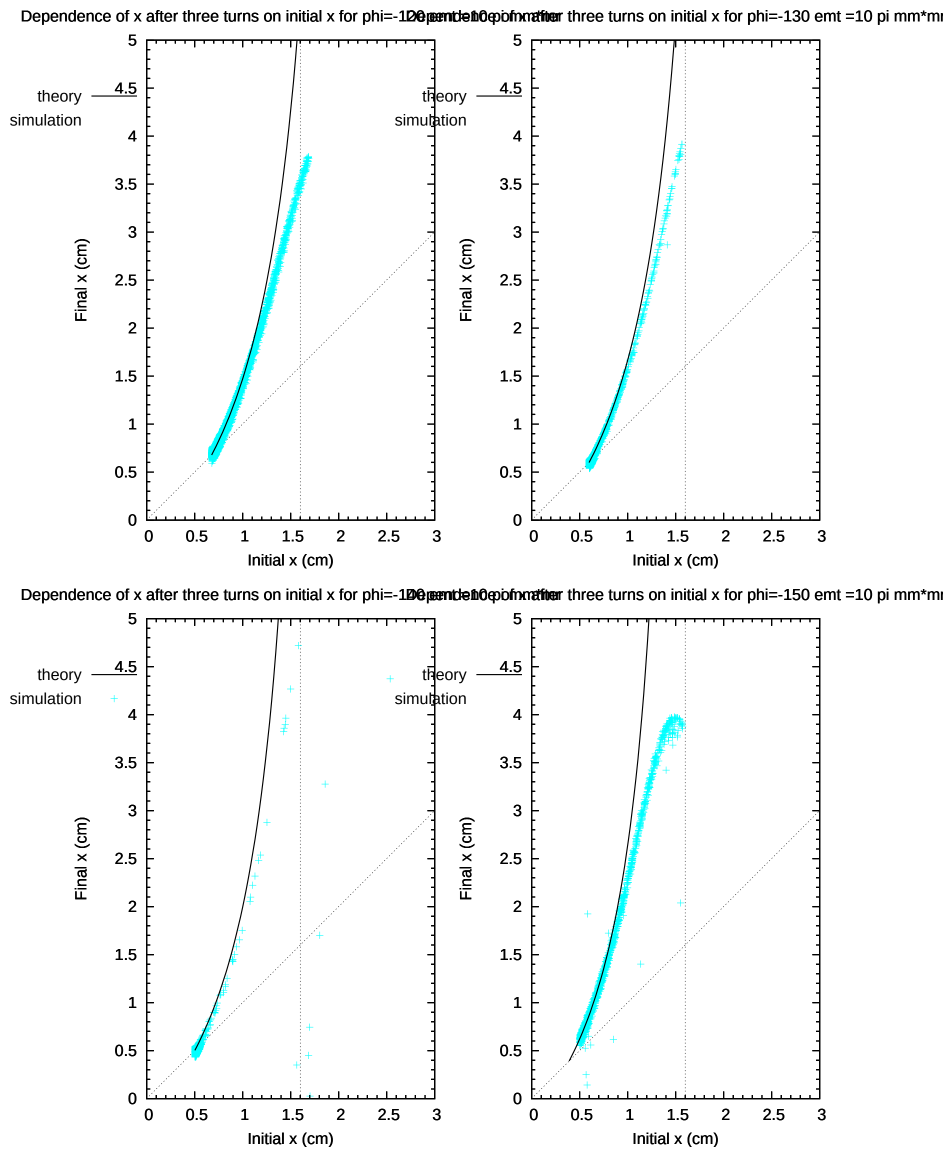
- Note: (a) G_4 and Δ must have opposite signs and (b) the stopband is $\pm 2|G_2|$.

Stepsize: third-integer; analytic



- For the "nominal" wire at 1.6 cm, at the extreme orientation, no particle crosses wire before its "reach" exceeds 5 cm. Even at $\varphi_0 = -120^o$, we need $\varepsilon_b \geq 30\,\pi$ mm-mr (or thereabouts) before it falls below this bound.
- Placing wire closer increases inefficiency, so there is a tradeoff.
- Beyond $\varphi_0 = -150^o$ particles would travel inwards, toward the center of the bunch, before being extracted.

Stepsize, third integer: theory and simulation

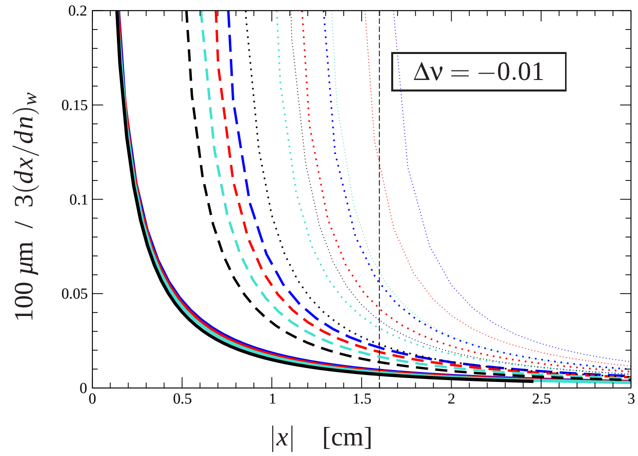


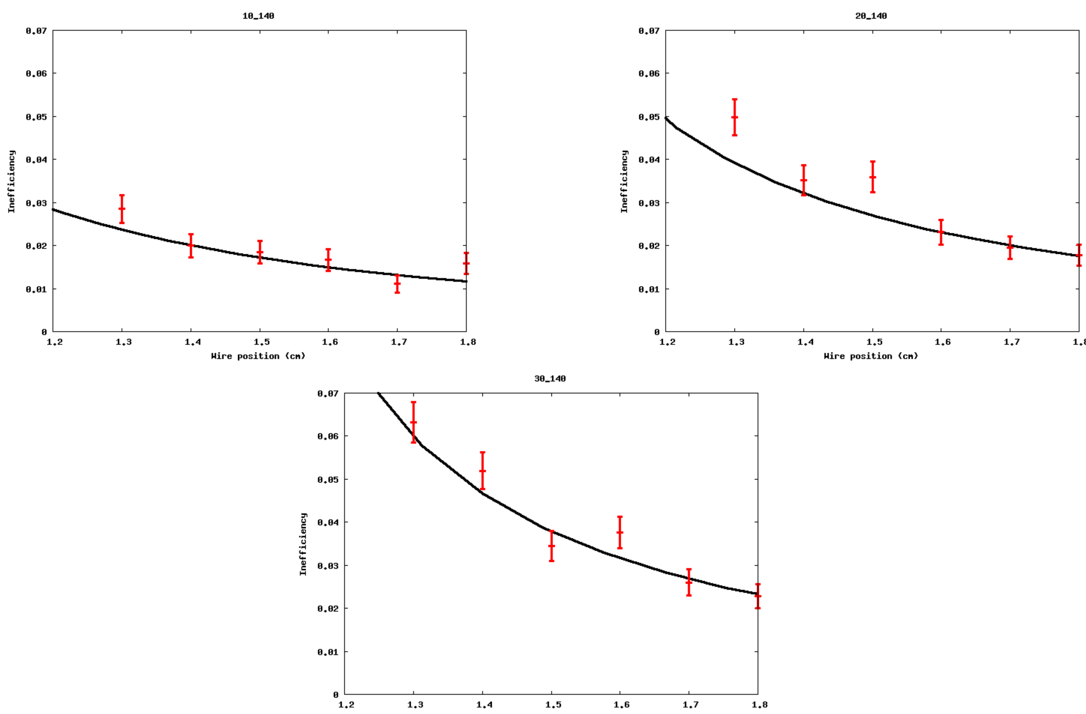
- Comparison of previously calculated stepsize curves with simulations.

Plots shown in the range $-150^\circ \leq \varphi_0 \leq -120^\circ$; $\varepsilon_x \cdot \beta\gamma = 10\pi$ mm-mr.

- Independent particle tracking; i.e. no space charge effects.
- As expected, theory overreaches, but agreement is better than expected.

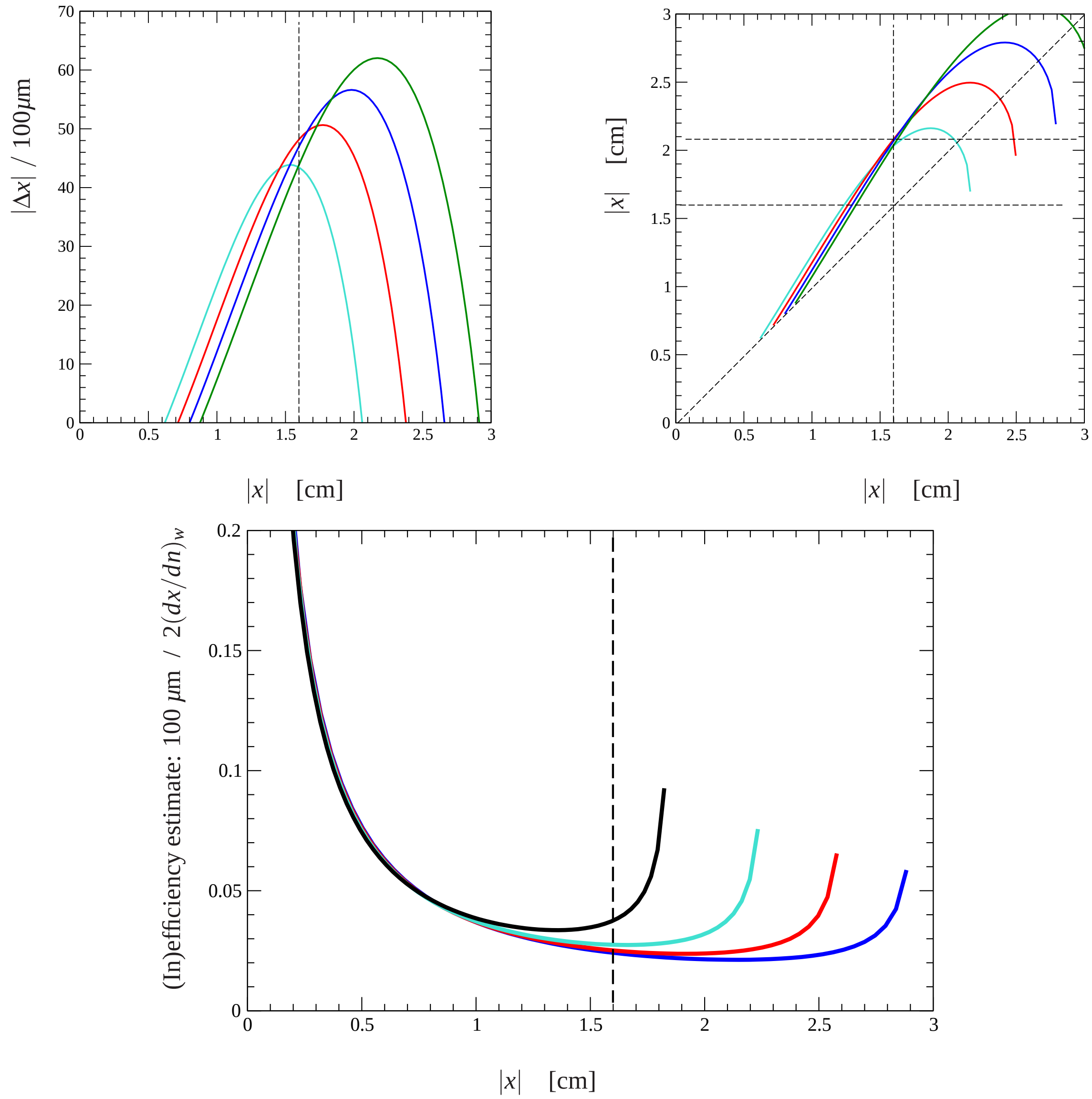
Inefficiency, third-integer: theory and simulation





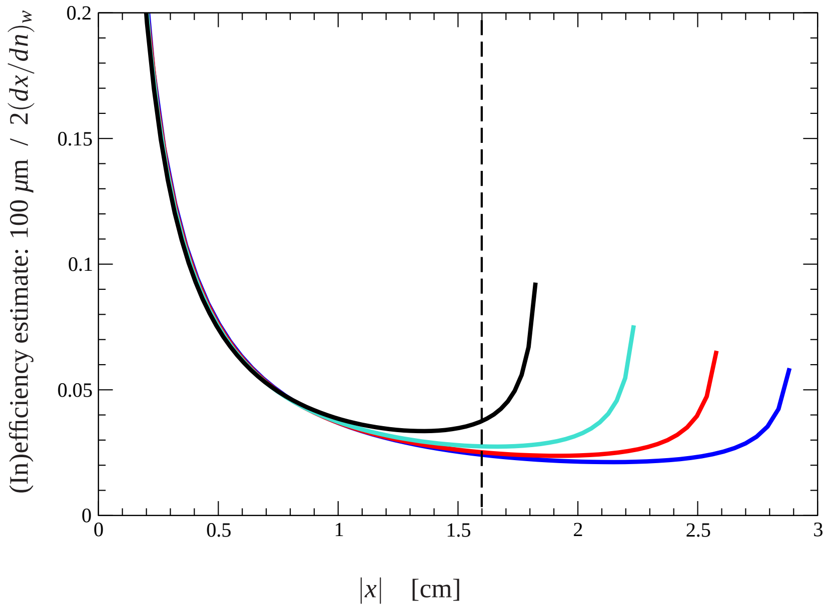
- Comparison of previously calculated inefficiency curves with third-integer simulations.
- Bottom line: Getting below 5% inefficiency at the septum should not be difficult; 2%-3% may be doable; below that cannot be guaranteed without reducing the wire size.

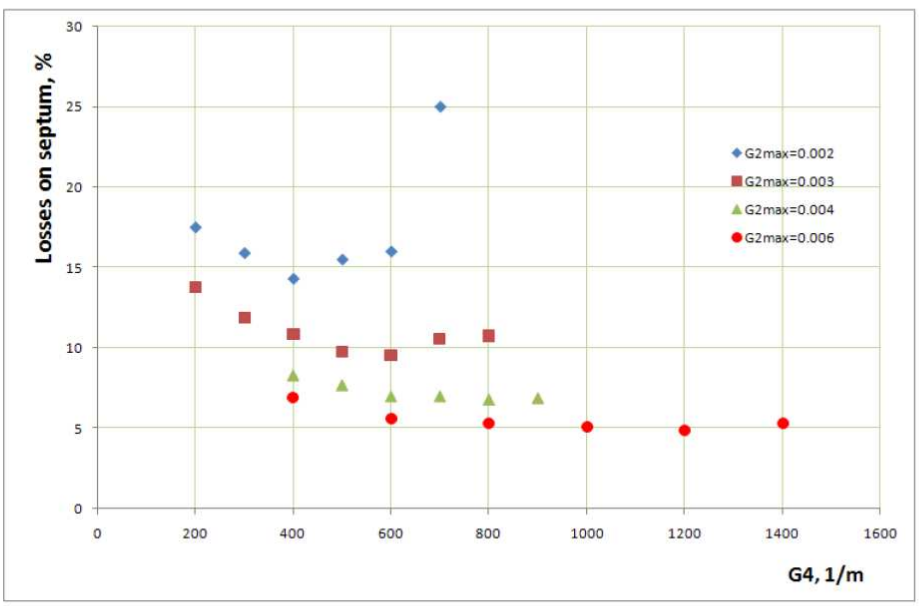
Stepsize and inefficiency: half-integer; quadrature



- Calculations carried out assuming the ratio, $\varepsilon_b/\varepsilon_c = \pi/(3\sqrt{3})$, for invariant emittance $\beta\gamma\,\varepsilon_b/\pi = 20, 30, 40, 50$ mm-mr.
- Initial tune: $(\Delta\nu)_{\text{initial}} = -0.02$. Two lobes of the 1/2 integer separatrix separated "horizontally" in (normalized) phase space: i.e. $\varphi_0 = \pm 180^{\text{o}}$.
- Standard 100 μm wire width; "nominal" placement, $x_w \approx -1.6$ cm.

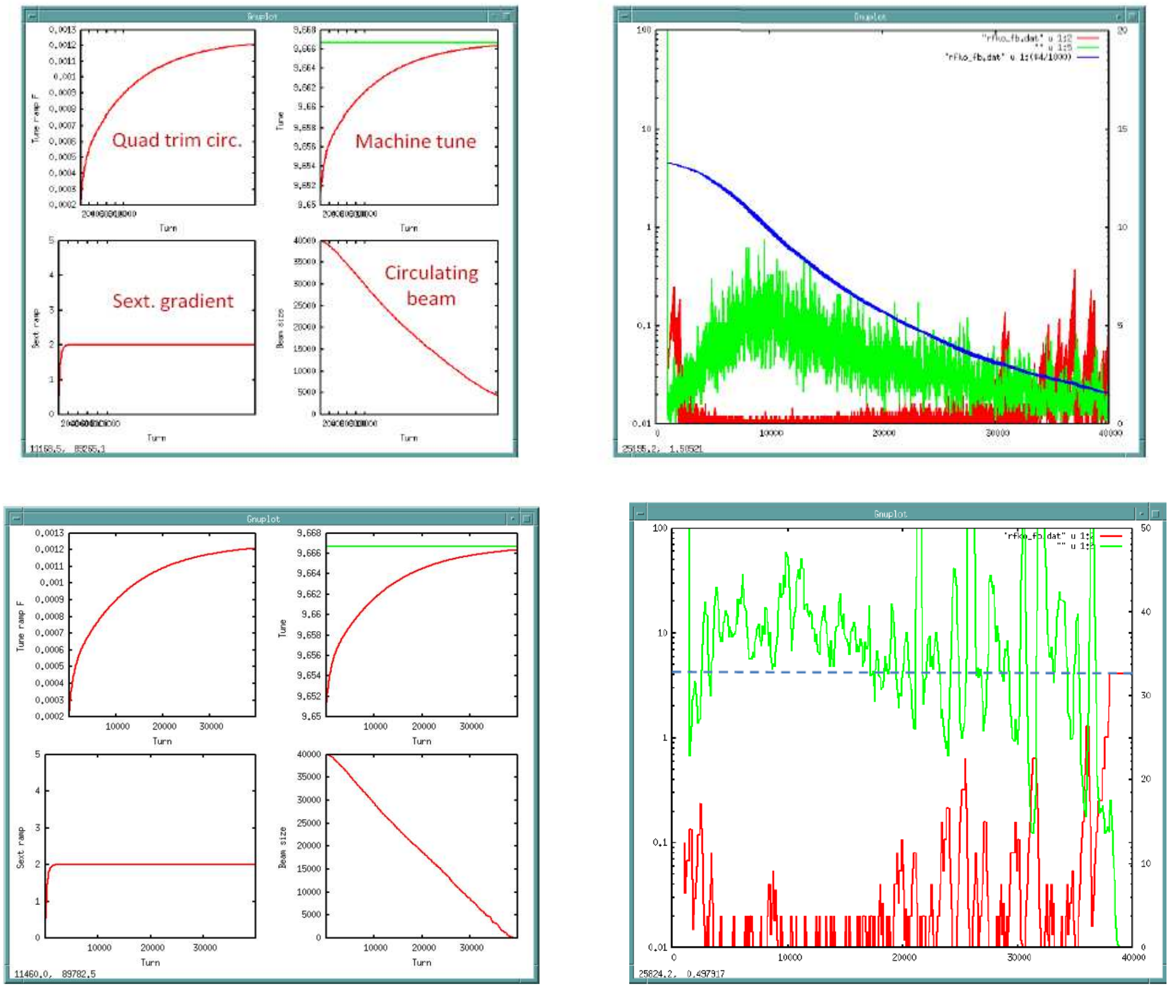
Inefficiency, half-integer: theory and simulation





- (Not quite) comparison of previously calculated inefficiency curves with half-integer simulations.

Simulation of third-integer extraction including space charge

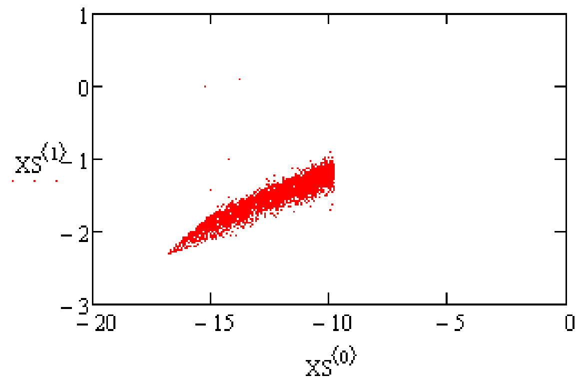


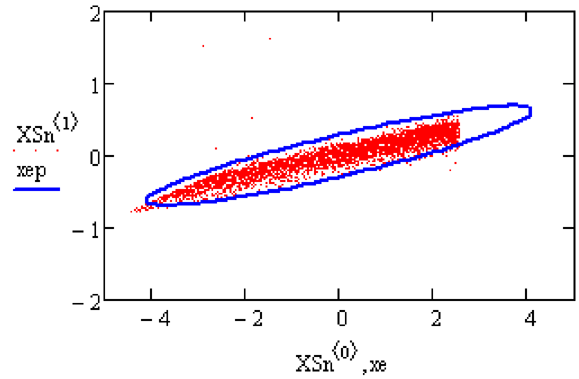
- On the left are plots of the quadrupole circuit ramp, tune, sextupole ramp, and beam intensity during the spill. On the right, the green trace shows the turn-by-turn structure of the spill, while the red follows the field strength, on a log scale, of the RFKO oscillator.

- RFKO by itself is not strong enough to control fully the spill rate; micro-adjustment of the tune ramp is needed.

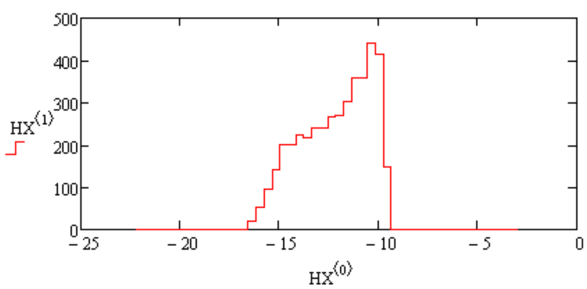
Extracted beam

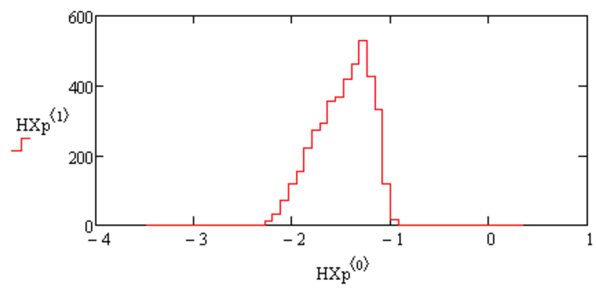
- Phase space





- Histograms





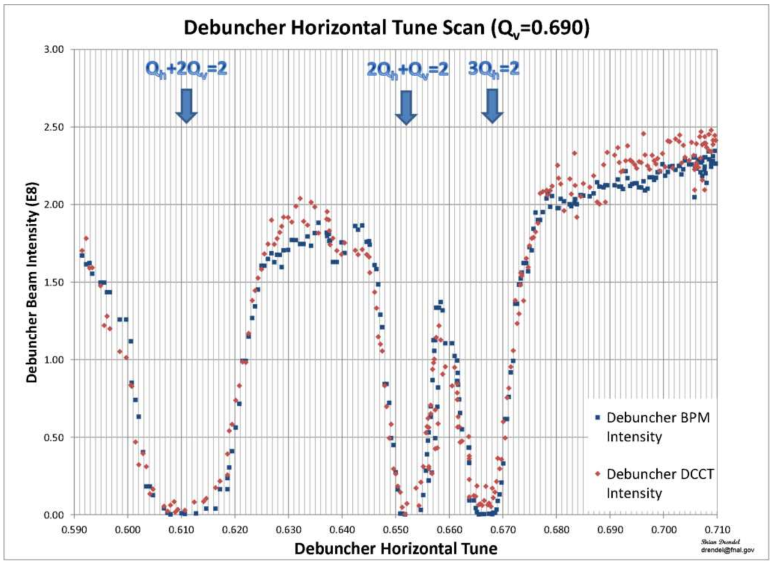
- Warning: plots made at septum, not lambertson.

- Histograms reveal distribution's skew.

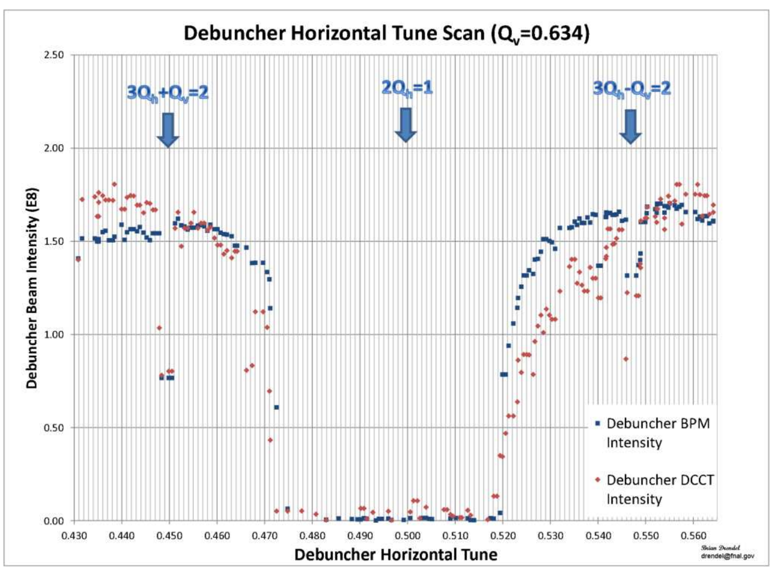
- With origin set at centroid, the ellipse enclosing 99% of the beam corresponds to $\beta_x = 14$ m, $\alpha_x = -0.57$, and $\varepsilon_x/\beta\gamma = 1.2\pi$ mm-mr.

Tune scans in Debuncher (w/ B.Drendel, J.Morgan)

- Near $\nu_x = 29/3$

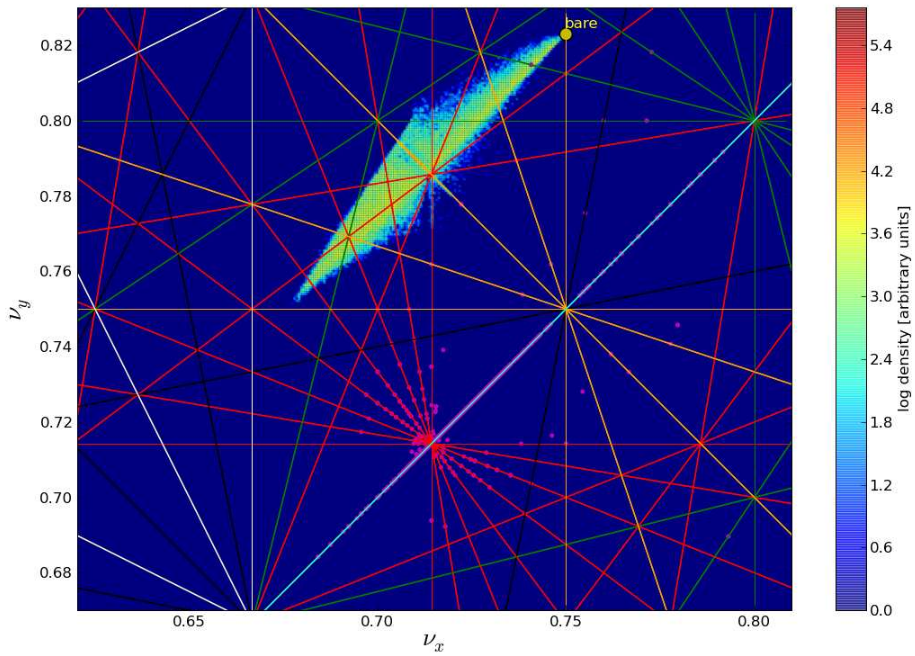


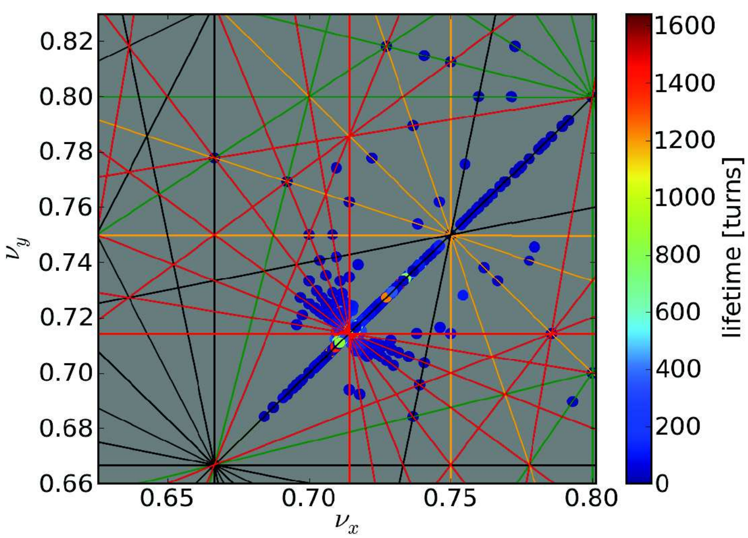
- Near $\nu_x = 19/2$



- The strong $(|\Delta\nu_x| < 0.025)$ half-integer stopband would have to be either nullified or mapped and controlled.

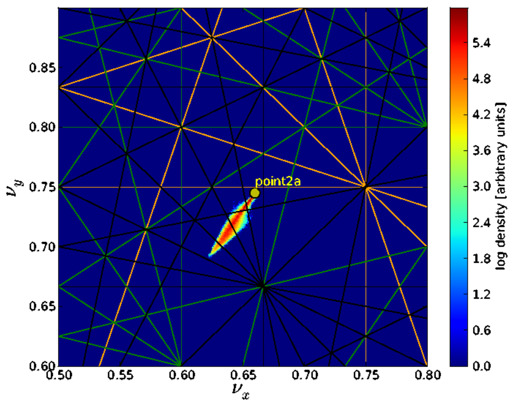
Original motivation for the tune scan

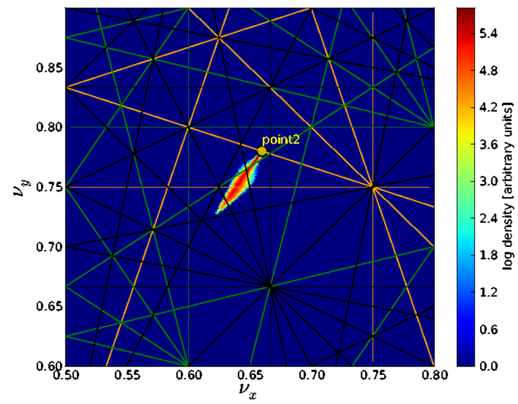




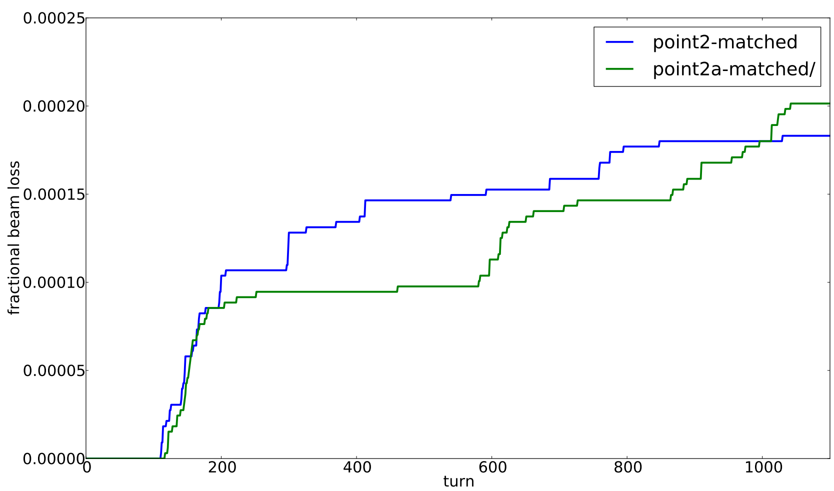
- Extreme simulation: protons lost along parasitic resonances.
- "Extreme" means (a) 12×10^{12} protons per bunch and (b) zero $\delta p/p$.
- Shown at Mu2e Collaboration Meeting on June 3, 2010.

More recent tune footprints





- Tune footprints have improved because of reduced intensity of the Hybrid scenarios and effect of Debuncher dispersion on non-zero $\delta p/p$ orbits.



- Loss ratio before extraction begins is now estimated at $\approx 10^{-4}$.

Where we are . . .

- **Lattice models.**
  ⇒ Accumulator and Debuncher lattice files written based on pbar source conceptual design reports are adequate (for now) to study half-integer and third-integer extraction.
  ◦ After CD-1 approval, more “dirt” will be added to the model: e.g. power supply ripple, misalignments, closed orbit control and error fields.
  ⇒ Control multipoles placed in two of the three straight sections; extraction septum and lambertson in the third. Care taken to maintain zero dispersion in straights.
- **Theory and quadrature.**
  ⇒ Basic theory understood and programs written to perform analysis and quadrature: e.g. stepsize and inefficiency. In reasonable shape, but not finished. Studies will continue.
- **Simulations.**
  ⇒ Independent particle simulations (CHEF), based on our Debuncher lattice model, adequately validate third-integer resonance theory; work continuing on the half-integer comparisons, but so far no “red flags.” Confident theory can be used for conceptual design.
  ⇒ Software for multi-particle simulations (ORBIT and SYNERGIA) “works” and is being used.
  ◦ But not without engaging challenges: e.g. parallel computing glitches; software instabilities.
- **Machine studies.**
  ⇒ Debuncher tune scans finished for now. MI half-integer studies devolved into studying the Main Injector rather than the half-integer resonance. Given three more months to work with, more may be done, but it depends on time and resource conflicts with competing activities.

Conclusions . . .

- This year's "hybrid" scenarios, with their reduced intensities, and large dispersion in the Debuncher arcs reduce the space charge tune footprint enough to make slow extraction conceivable.
- Recommend RFKO be added to Fermilab's suite of control devices to "heat" beams with initially small emittances.
- Have (reasonably) successfully simulated slow third-integer extraction in the presence of space charge. Space charge still needs to be added to a half-integer simulation. Continuing analysis needed for both.
- A few hundred to (less than) a thousand turns suffice to acclimate an injected bunch to its separatrix. (The time budget of the Hybrid scenarios allow for several thousand.)
- For perfect model, currently estimate loss ratio of a few 10^{-4} before extraction begins, presumably due to parasitic resonance lines.
- Roughly, 3%-5% of protons will be lost hitting the septum's wire. This is more problematic for small emittances and half-integer resonance.
- Currently, third integer preferred to half-integer.
- If the instability studies hold up, chromaticity can be small. This will reduce reduce "blurring" the separatrix due to $\delta p/p$.
- Two cost estimates done: six sextupoles will cost $\approx$ \$340,000; RFKO, $\approx$ \$59,000-\$160,000, depending on power considerations. (Thanks to Dave Harding, Tom Gardner and Dave Wildman.)

Concerns

- Finish septum and lambertson design bounds based on stepsize, inefficiency, and aperture considerations.
- Hardware specification list(s) and cost estimate(s) barely begun. Must be finished before CD-1 review.
- Map distributions of losses around the ring and (phase space) protons injected into transfer line.
- What is the real requirement on turn-by-turn stability??? (Meeting to take place next month.)
- What instrumentation and control (if any) can achieve this requirement?
- Integrate better (or at all) with extraction beamline.
  ⇒ Missing segment: lambertson to the “stub.”
  ⇒ 6D phase space distributions and histories at entrance to extraction line.
- Finish comparison and interpretation of theory and independent particle simulations for half-integer inefficiency (and stepsize).
  ⇒ Recommend design parameters based on these.
- No simulation yet of half-integer resonance extraction with space charge included.
  ⇒ How much should this be pushed? Should we deprecate half-integer extraction and be done with it?
- Engineers and scientists needed: hardware design, cost estimates, instrumentation and controls.

EXTRA VIEWGRAPHS

ALL VIEWGRAPHS BEYOND THIS POINT ARE “EXTRA.”

Activities

Three facets:

- Orbit theory of resonance:
  - ⇒ Analysis: substance identical to 25-40 forty years ago but different form.
  - ⇒ Quadrature: a few calculations can be done: stepsize, ”(in)efficiency”
- Simulations
  - ⇒ Independent particles: to test theory. (Missing terms can haunt you.)
  - ⇒ Multiparticle: including space charge.
- Experiments (i.e. machine studies)
  - ⇒ Tune scans of Debuncher.
  - ⇒ Half-integer extraction from Main Injector.

Underneath them all:

- “Clean” accelerator models:
  - ⇒ MAD v.8 lattice files written for Debuncher and Accumulator using descriptions written in *The Fermilab Antiproton Source Design Report* (c.1982).
  - ⇒ Debuncher file later translated into Optim syntax too.
- Software:
  - ⇒ MAD: redesigning phase advances and lattice functions.
  - ⇒ ORBIT: 2 D & 2.5 D space charge calculations
  - ⇒ SYNERGIA: 2 D & 3 D space charge calculations
  - ⇒ CHEF: build model from MAD description; independent particle tracking; construct transfer maps for SYNERGIA
  - ⇒ OPTIM: construct transfer maps for ORBIT

Hardware costs

• SEXTUPOLES (third-integer) For third-integer extraction we are proposing two families of three bussed sextupoles possessing the following properties:
○ Integrated strengths (for each): $|B''l|$ is in the range 30-110 T/m, depending on assumptions going into various scenarios; approximately 50 T/m is a reasonable estimate.
○ Length: 25-50 cm.
○ Minimum horizontal aperture: about 6-8 cm $\boxed{???}$
○ Ramp time: under some scenarios, sextupoles would be DC, not ramped. Under others, they would have to go from zero to full field in something like 5 msec.
○ We assume no constraints on outside dimensions.
○ Field quality: the canonical ”few parts in 10^4 at one inch” is expected to be adequate - possibly even better than needed.
The estimated costs required to construct six such magnets are:

```
Material:  $27,720
Labor   : $104,640
EDIA    : $146,496
Tooling :  $52,000
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Total   : $340,000
```

• RFKO oscillator An important new component - definitely to be used for third-integer extraction and most probably for half-integer as well - will be a horizontal electric field oscillator to implement RF knockout. We expect that a Tevatron style damper would accomodate its requirements:
○ Frequency: 3 kHz to 10 MHz
○ Maximum field amplitude: 8.6 kV/m
○ Length: $\approx$ 1.4 m
○ Gap: 6.4 cm
If so, a spare is available at no “extra” cost for construction. However, two power amplifiers of 800 Watts each will cost $59,000; or two 1.5 kWatt commercial amplifiers would cost $160,000. Those are hardware costs alone.

• NO COST ESTIMATES for septum and lambertson, trim quadrupoles (tune control), Octupoles and harmonic quadrupoles (half-integer), diagnostics and control.

Documents in Mu2e docdb

Documents were added to the Mu2e document database throughout 2009-2010. As of September:

415-v3	Accumulator & Debuncher Overview
422-v1	Third Integer Extraction from the Debuncher
423-v1	3rd Integer Extraction from Debuncher Progress Report, Part II
457-v1	Phase Space of Tune Scan
512-v0	Space Charge Simulations for the Mu2e Experiment at Fermilab
537-v1	Space Charge Update
549-v1	Space Charge Calcs Update
555-v1	Half-Integer Resonant Extraction from the Debuncher
556-v3	Preliminaries toward studying resonant extraction from the Debuncher
576-v1	An Alternative Approach to 1/2-Integer Resonant Extraction Using a Supplementary 0th-Harmonic Quadrupole Circuit.
673-v1	Debunch_20081112.lat
744-v1	Proton Delivery
768-v4	Documents on resonant extraction
775-v1	On using the RFKO method for resonant extraction
878-v3	Parameters for simulating extraction from the Debuncher
879-v1	March 12, 2010: Meeting with controls and machine experts re extraction studies.
980-v1	Procedure for preparing a simulation of half-integer extraction
982-v1	Status of Extraction Studies
1021-v1	Step size, efficiency, and the septum; notes from quadrature.
1024-v1	Status: extraction studies from Main Injector.